Performance Optimization of a Stirling Pulse Tube Cryocooler with an Active Displacer

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ABSTRACT

An in-line Stirling pulse tube cryocooler with an active displacer has been built and tested. An active displacer allows the mass flow and the pressure variation at the cold end of the pulse tube to be easily adjusted for optimum performance. The effect of varying the active displacer phase and stroke on cryocooler performance was examined experimentally. It is demonstrated that both cooling power and efficiency have optimum displacer phase and stroke values. The pulse tube cryocooler can deliver up to 4 W of cooling at 80 K with an input power of 100 W when operating at optimal displacer phase and stroke. Moreover, a numerical Sage model was used to assess how this variation in displacer phase and stroke affects the mass flow and pressure variation at the cold end. It is shown that the variation in displacer phase affects the cryocooler performance by varying the amplitude of the mass flow at the cold end. On the other hand, changes to the displacer stroke lead to variations in both phase and amplitude of the mass flow at the cold end.

INTRODUCTION

One of the key requirements for successful operation of a Stirling pulse tube cryocooler (SPTC) is to ensure the correct relationship between the mass flow and the pressure variation at the cold end [1]. This is usually achieved via the use of an orifice, an inertance tube or a warm end displacer. The major advantage with using an orifice or an inertance tube is that they do not have any moving components in the cold head assembly. The downside is that it is difficult to ensure the correct relationship between mass flow and pressure at the cold end. A warm end displacer on the other hand allows this relationship to be controlled. Moreover, the expansion power at the warm end of the pulse tube, which is otherwise dissipated as heat when using an orifice or an inertance tube, can be recovered via the displacer. This can help the SPTC operate more efficiently [2].

An in-line SPTC with an active displacer has been developed at the Cryogenic Engineering Group at the University of Oxford in collaboration with Honeywell Hymatic. In this study an overview of its performance is presented along with displacer phase and stroke sensitivity analysis. Furthermore, a numerical Sage [3] model is used to better understand the trends observed by looking at the mass flow and pressure pulse at the cold end.

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EXPERIMENTAL LAYOUT AND INSTRUMENTATION

Fig. 1 shows a schematic of the SPTC along with the instrumentation. The cryocooler consists of:

- A dual piston oil-free linear compressor which acts as a pressure wave generator with a typical operating frequency of 60 Hz (comp in Fig.1).
- A regenerator filled with stainless steel mesh – 400 wires per inch (reg in Fig.1).
- A cold end heat exchanger filled with copper mesh – 50 wires per inch (CHX in Fig.1). The cold end temperature was recorded using a platinum resistor thermometer (PRT) and a silicon diode cryogenic temperature sensor. A PID temperature controller was used to maintain a user defined cold end temperature.
- A pulse tube (PT in Fig.1).
- A warm end heat exchanger at ambient temperature which is also filled with copper mesh – 50 wires per inch (WHX in Fig.1).
- An oil free single piston active displacer that ensures the correct relationship between mass flow and pressure pulse can be achieved (disp in Fig.1).
- The cold head assembly was housed inside a vacuum chamber in order to minimise convective losses. Fig. 2 shows the cold head assembly in more detail.

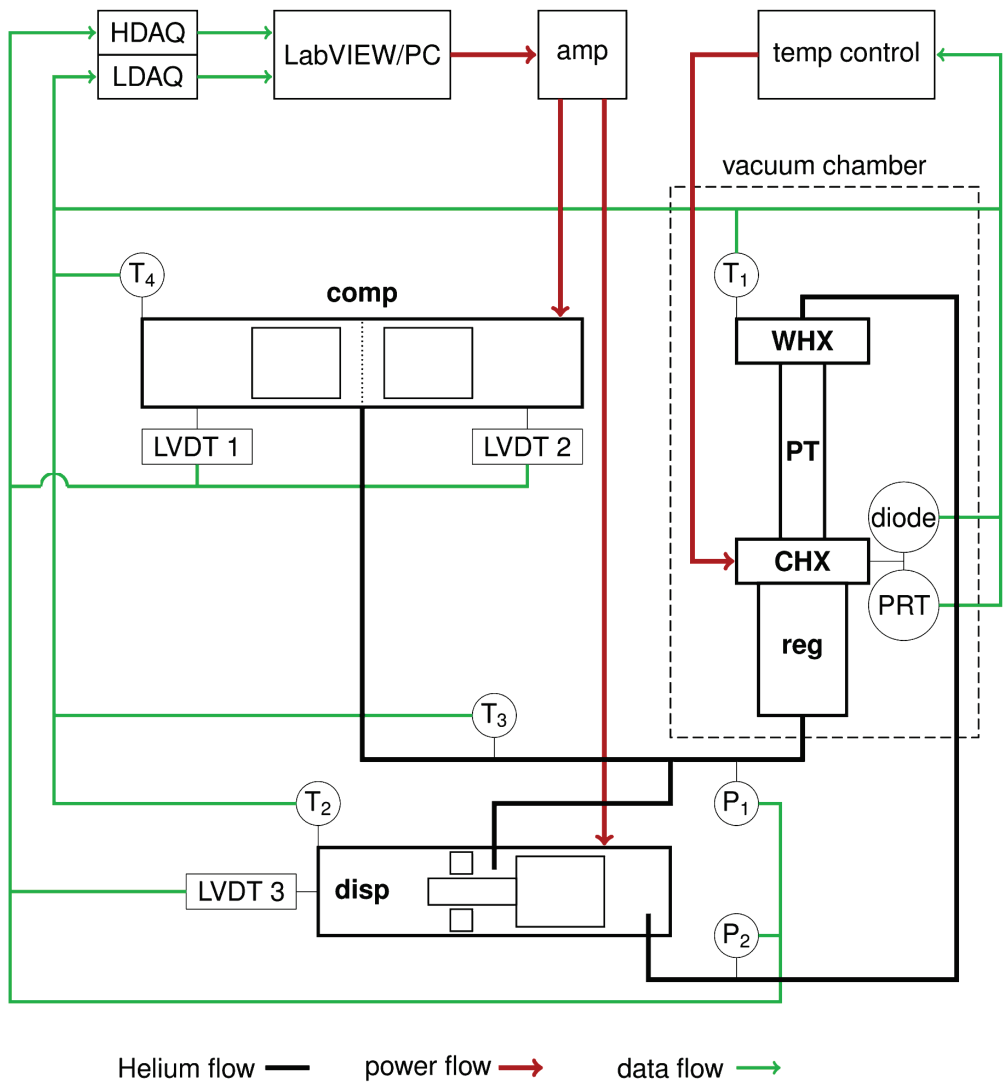

Figure 1. SPTC experimental layout and instrumentation with abbreviations **comp** for linear compressor, **disp** for active displacer, **reg** for regenerator, **PT** for pulse tube, **CHX** for cold end heat exchanger, **WHX** for warm end heat exchanger, **amp** for amplifier, **HDAQ** for high speed data acquisition and **LDAQ** for low speed data acquisition, **PRT** for platinum resistor thermometer, **T** for thermocouple and **P** for pressure transducer.

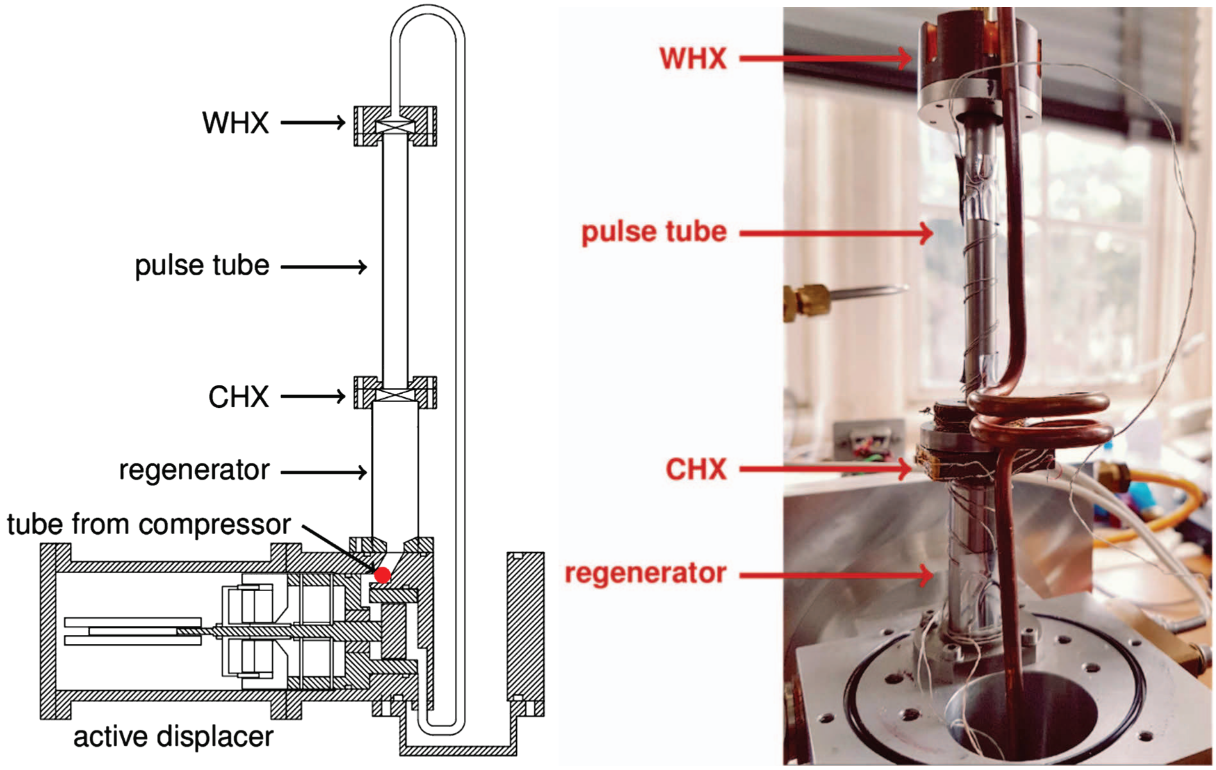

Figure 2. The cold head assembly with the vacuum chamber removed and before it was wrapped in radiation shields. The drawing shows how the back space of the active displacer is connected to the warm end of the regenerator. The location where the connecting tube from the linear compressor joins the cold head assembly is also shown.

The compressor and displacer motion were controlled via user defined sinusoidal waveforms using LabVIEW. These were amplified and then delivered to the components. The displacements were monitored using linear variable differential transformer (LVDT) displacement transducers. Pressure transducers were also used to monitor the pressure either side of the active displacer. These data were recorded via the high-speed data acquisition (HDAQ) card at a sampling rate of 5 kHz. Moreover, thermocouples were used to record component temperatures at a sampling rate of 10 Hz via the low speed data acquisition (LDAQ) card.

SENSITIVITY TO DISPLACER PHASE AND STROKE

Optimum Values

By varying the active displacer motion relative to the linear compressor, the behavior of the mass flow at the cold end can be altered. In order to assess the SPTC performance sensitivity to the displacer motion, a number of tests were carried out. These tests were carried out at a fill pressure of 28 bar and with an operating frequency of 60 Hz. During these tests, the cold end was maintained at 80 K and the cooling power was recorded. Initially, a constant displacer stroke of 5 mm was used and the displacer phase (relative to compressor motion) was increased from 30º to 65º. Subsequently, a constant displacer phase of 40º was used and the displacer stroke was changed from 4 mm to 6.2 mm. A constant compressor stroke was used throughout. The results are shown in Fig. 3. Both cooling power and specific power (watts per watt) are shown.

The results reveal optimum values for both displacer phase and stroke. The phase sensitivity plot suggests an optimum phase value of around 50º for maximum cooling power. Optimum efficiency (based on lowest watts per watt) occurs at a lower value of 40º. In terms of displacer stroke, maximum cooling power occurs at around 6 mm with maximum efficiency at around 5 mm. Noticeably, the peaks in both plots are broad and this suggests that a small deviation away

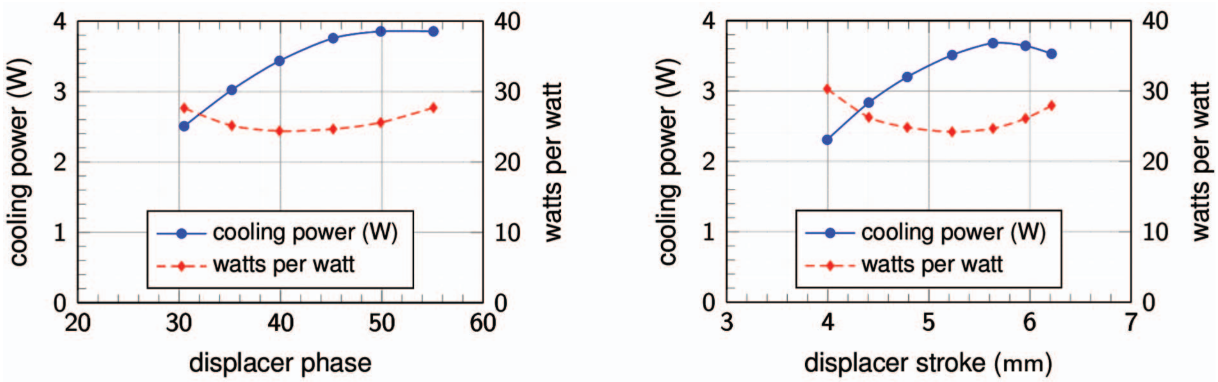

Figure 3. SPTC performance sensitivity to active displacer phase and stroke with a fill pressure of 28 bar and an operating frequency of 60 Hz. A constant compressor stroke was used.

from the optimum phase and stroke values will not have a significant effect on the SPTC performance.

Performance at Optimum

Having discovered the optimum displacer stroke and phase values, further tests were carried out to map the SPTC performance at different cold end temperatures ranging from 70 K to 120 K. For these tests a constant displacer phase values of 40° and a constant displacer stroke value of 5 mm was used. These were the optimum values in terms of highest efficiency at 80 K (see Fig. 3). The fill pressure was 28 bar and the operating frequency was 60 Hz. The results are shown in Fig. 4. The SPTC was designed to operate at 80 K where it delivers 4 W of cooling with an input power of 100 W.

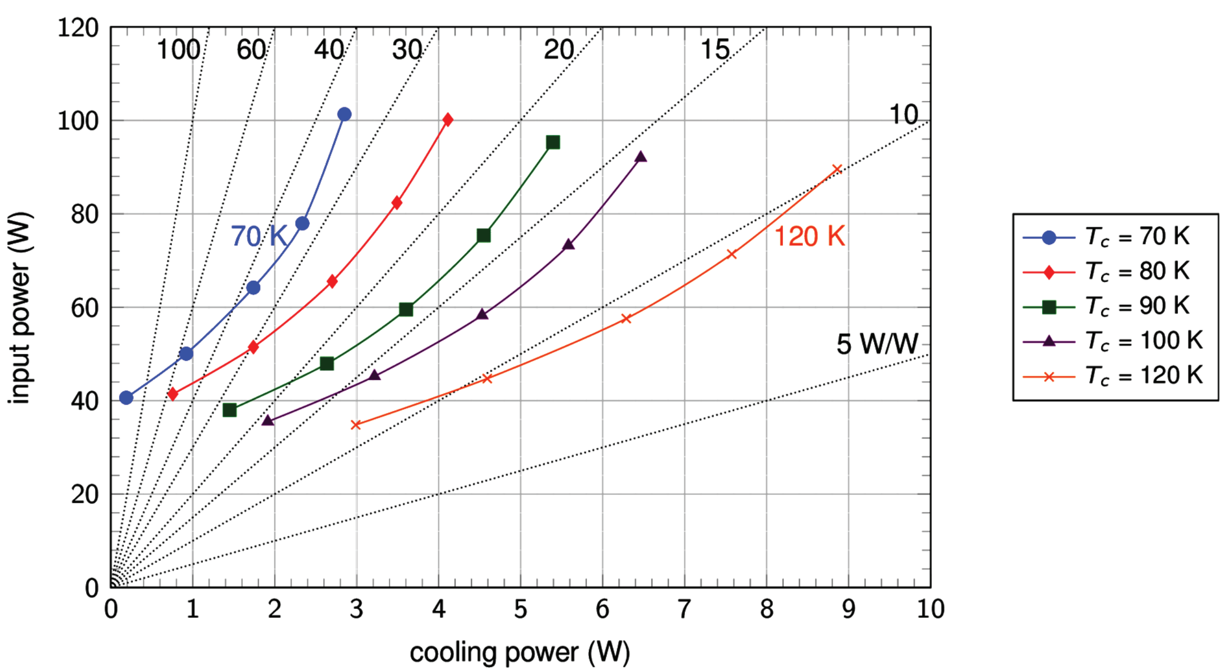

Figure 4. SPTC performance at optimum displacer phase and stroke with a fill pressure of 28 bar and an operating frequency of 60 Hz. The dotted lines represent contours of specific power (W/W).

WHAT IS HAPPENING AT THE COLD END?

In order to better understand the mechanism behind the variation in SPTC performance observed in Fig. 3, a numerical Sage model of the in-line SPTC was created. The values for the reference temperatures in the Sage model were set to the values recorded via thermocouples in the experiments. The Sage model allows us to study the behavior of the mass flow and pressure variation at the cold end as the displacer phase and stroke is varied. Figure 5 shows the behavior of the mass flow and pressure variation at the cold end according to Sage when a 40º displacer phase angle and a 5 mm displacer stroke was used. According to Fig. 5 this leads to a peak-to-peak mass flow value of $|\dot{m}| = 3.3$ g/s and a mass flow phase angle relative to pressure of $\varphi_{pm} = 11º$ (based on the first harmonic). Using the Sage model, the behavior of the mass flow at the cold end at different displacer phase and stroke values was studied. The variation in peak-to-peak mass flow and the mass flow phase angle (relative to pressure) is shown in Fig. 6.

According to the Sage results, increasing the displacer phase has a significant effect on the peak-to-peak mass flow where it more than doubles in magnitude. On the other hand, the mass flow phase value changes by only 10º. This appears unintuitive at first, since a change in displacer phase is expected to predominantly change the mass flow phase. However, one should bear in mind that as well as having a connection from the displacer compression space to the warm end of the pulse tube, the back space of the displacer is connected to the warm end of the regenerator (see Fig. 2). This is the main cause for the significant variation in peak-to-peak mass flow observed. Moreover, the results suggest that most of the increase in cooling power observed in Fig. 3 is due to the increase in peak-to-peak mass flow at the cold end. Having said that, the mass flow phase value is

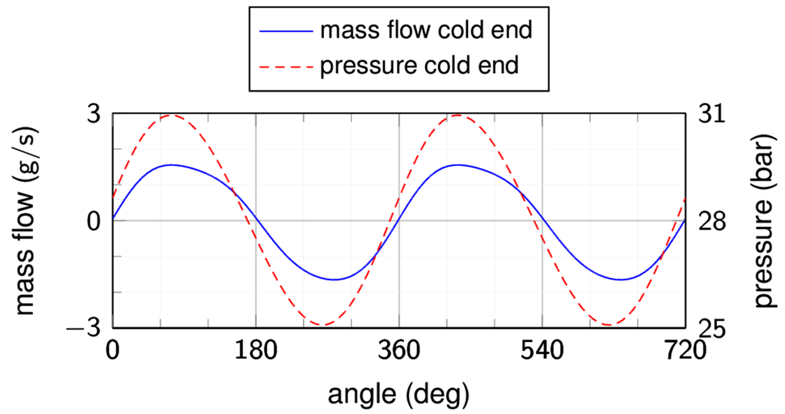

Figure 5. Mass flow and pressure pulse at the cold end according to Sage with displacer phase and stroke values of 40º and 5 mm, respectively, and a cold end temperature of 80 K.

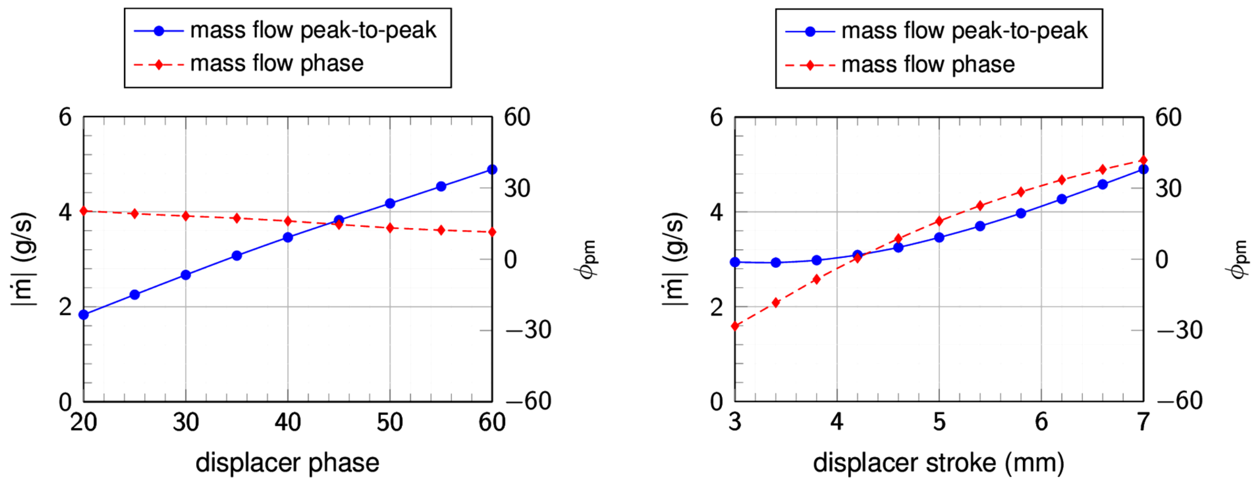

Figure 6. Variation in mass flow peak-to-peak and phase for different displacer phase and stroke values according to Sage.

also important, since the cooling power in Fig. 3 reaches a maximum around 50º, whereas the peak-to-peak value is still rising even at 60º. This is because the mass flow phase has drifted away from its optimum value, which appears to be around φ_{pm}= 15º.

On the other hand, changing the displacer stroke value leads to significant variations in both peak-to-peak mass flow and mass flow phase. The peak-to-peak mass flow has almost doubled and there is a 60º variation in the mass flow phase relative to pressure pulse. In this case, the variation in cooling power observed in Fig. 3 appears to be predominantly due to the deviation away from the optimum mass flow phase value of φ_{pm} = 15º.

CONCLUSIONS

This study focused on the performance optimization of an in-line SPTC with an active displacer. The key findings are:

1. The active displacer has optimum phase and stroke values for both cooling power and efficiency (watts per watt).
2. The cooling power and efficiency peaks are broad and the two optimums are close. Hence, careful selection of displacer phase and stroke can simultaneously ensure high efficiency and cooling power.
3. According to Sage, the variation in cooling power as a function of displacer phase is predominantly due to changes in the peak-to-peak mass flow at the cold end.
4. According to Sage, the variation in cooling power as a function of displacer stroke is predominantly due to deviation away from the optimum mass flow phase (relative to pressure pulse) at the cold end.

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